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Response of crop yield and nitrogen use efficiency for wheat-maize cropping system to future climate change in northern China

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ABSTRACT

Climate change and excessive fertilization will threaten the crops yields and nitrogen utilization in coming decades. The aim of this study is to quantify the response of crop yields and nitrogen use efficiency (NUE) to different fertilization strategies and climate change scenarios in the northern China by 2100 using the process-based SPACSYS model. The model was calibrated and validated with the data from four long-term experiments with winter wheat (*Triticum Aestivium* L.) and summer maize (*Zea mays* L.) rotation in the northern China. Five fertilizer treatments based on the long-term experiments were chosen: non-fertilizer (CK), a combination of mineral nitrogen, phosphorus and potassium (NPK), NPK plus manure (NPKM), a high application rate of NPKM (hNPKM) and NPK plus maize straw (NPKS). The model simulations and projections were performed under four different climate change scenarios including baseline, RCP2.6, RCP4.5 and RCP8.5. Validation demonstrated that SPACSYS can adequately simulate crop yields, N uptake and annual NUE for the wheat–maize rotation. Without considering the impact of cultivar change, maize yield would increase by an average of 8.5% and wheat yield would decrease by 3.8%, and the annual NUE would decrease by an average of 15% for all fertilization treatments under RCP climate scenarios compared with the baseline. This might be the interactive effects among elevated CO_2 concentration, more concentrated and intensive rainfall events, and warming temperature. For each climate scenario, manure amendment could alleviate the negative influences of future climate change on crop growth and nitrogen utilization, given that manure applied treatments had higher soil organic matter and persistent supply of nutrients, which resulted in a more stable crop yield and N removal by wheat and maize than other treatments. In addition, the highest and most stable annual NUE (38.70–52.78%), crop yields and N removal were found in hNPKM treatment until 2100. The results could provide a reference for nitrogen fertilization in study regions to improve crop yield and nitrogen use efficiency and minimize environmental risks in the future.

1. Introduction

Nitrogen use efficiency (NUE) is a key indicator to assess the N uptake by crops and can be used to address environmental pollution from mineral N input (Duan et al., 2011; Lassaletta et al., 2014; Raun and Johnson, 1999; Zhang et al., 2015). It has been widely reported that NUE of main crops approximately reach to 30% in China, which is far lower than that in United States (approximately 65%) and other developed countries (Duan et al., 2014; Lassaletta et al., 2014; Liu et al., 2010b). Especially in the north of China, a main cereal production area dominating by a wheat-maize rotation (Li et al., 2015; Xiao and Tao, 2016; Zhao et al., 2009), NUE is only about 16–18% due to excessive use of mineral N from 1987 to 2015 (*ca.* 200% of increment) (Cui et al., 2010; National Bureau of Statistics of China, 2016). Improper utilization of mineral N led a huge N loss to the environment *via* greenhouse gas (GHG) emissions, ammonia volatilization and leaching with the fact

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Table 1
Information of location, climate type and initial soil properties of four experimental sites.

Items	Changping (CP)	Zhengzhou (ZZ)	Xuzhou (XZ)	Yangling (YL)
Starting year	1990	1990	1981	1990
Location	116°15′22″E 40°13′22″N	113°40′00″E 34°47′00″N	117°17′30″E 34°17′00″N	108°00′48″E 34°17′51″N
Climate type	Semi-humid	Semi-humid	Semi-humid	Semi-arid
Annual temperature, °C	11.0	14.5	14.0	13.0
Annual precipitation, mm	600	632	860	575
Annual evaporation, mm	2310	1450	1870	993
Irrigation[a], mm	300	225	–	270
Irrigation times	2(wheat) 2(maize)	3(wheat) 2(maize)	–	1(wheat) 2-3(maize)
Aridity index	0.65	0.83	1.16	0.84
Plot size, m^2	200	400	33.4	196
Replicates	1	1	4	1
Soil type	Haplic Luvisol	Calcaric Cambisol	Calcaric Cambisol	Cumulic Anthrosol
Initial SOC[b], g kg^{-1}	7.10	6.60	6.26	7.44
Total N[b], g kg^{-1}	0.79	0.65	0.66	0.83
Available N, g kg^{-1}	0.05	0.08	0.07	0.06
Total P[b], g kg^{-1}	0.69	0.65	0.74	0.83
Olsen P, mg kg^{-1}	4.6	6.5	12.0	9.6
Total K[b], mg kg^{-1}	14.6	16.9	22.7	21.6
Available K, mg kg^{-1}	65.4	74.0	62.0	194.0
pH	8.2	8.3	8.2	8.6
Bulk density, g cm^{-3}	1.58	1.55	1.25	1.35
Clay, %	10	13	6	17

[a] Both wheat and maize season had irrigation.
[b] SOC means soil organic carbon; N means nitrogen; P means phosphorus; K means potassium.

that cereal crop yields however did not increase obviously (Driscoll et al., 2003; Zhang et al., 2015; Zhu and Chen, 2002). Thus, maintaining a high productivity level while promoting NUE should be achieved urgently for China's agricultural sustainability.

Future climate has been projected that temperature and precipitation will increase by 1.0–5.0 °C and 9–11%, respectively, and CO_2 concentration will increase to 560 ppm at the end of this century (Ju et al., 2013; Meehl et al., 2007), which further brings more challenges for agricultural production (Challinor et al., 2014; Graß et al., 2015). It has been reported that future climate change would be highly likely to have a negative impact on agricultural productivity in the northern China (Xiao and Tao, 2016). It has been proved that changes in temperature, precipitation, solar radiation and CO_2 concentration would alter NUE of crops through the changes in crop N removal and N losses from a plant-soil system (Dahal et al., 2014; Fujimura et al., 2015; Ma et al., 2010; Meng et al., 2014). Thus, clarifying the effects of climate change on crop yields and NUE is highly needed for maintaining agricultural productivity and reducing N losses for food security and a clean environment in the northern China.

Previous studies indicated that grain yield and NUE for the main crops can be maintained or increased by the appropriate fertilization strategies reasonably (Benbi and Biswas, 1997; Chen et al., 2013). It was reported that NUE of wheat in the treatment with balanced application of N, P and K fertilizers (NPK, with an average of 49.5%) was significantly higher than that in the treatment with N applied alone (with an average of 10.5% and an annual decreasing rate of 1.2%) in four typical soils of China (Yan et al., 2011). In addition, mineral fertilizers combined with animal manure resulted in a higher and stable yield compared with NPK after 15 years fertilization for wheat and maize in China, and the highest mean NUE (49%) was from NPKM treatment (Duan et al., 2014). A long-term experiment in the Northeast of China indicated that 18 years of manure or straw incorporation improved 218% and 192% of maize yield compared with no fertilization, respectively (Zhang et al., 2012). It also indicated that NPK plus manure led to the highest soil fertility, which further promoted the productivity and stability of wheat and maize yields at Xuzhou (Jiang et al., 2006).

Simulation models have been used for quantitatively assessing the effects of future climate change on crop growth and N utilization as field or laboratory experiments could be time consuming and expensive (Dueri et al., 2007; Li et al., 2014, 2017; Zhang et al., 2016c). However, studies on modeling N utilization mainly focused on N transfer progresses in the plant-soil systems, and very rare studies focused on simulation and prediction of NUE in agricultural systems (Gabrielle et al., 2002; Hansen et al., 1991; Kaur et al., 2012; Probert et al., 1998). The SPACSYS model that is process-based and at field scale, provides detailed processes of plant growth and development, carbon (C) and N cycling and water redistribution (Wu et al., 2007, 2015) and has been proved that the model has capable on simulating and predicting the impacts of climate change on the grain yields of wheat and maize, the GHG emissions and the stocks of soil C and N in China (Zhang et al., 2016a,b,c). Although the model has been applied in various environmental conditions and field management practices, it is still needed to validate it with more experimental datasets and test it with broader climatic conditions, especially the projected climates. Thus, it would be helpful to use the model to address how cereal crop growth and N utilization responds to climate change with different fertilization strategies in the north of China.

Our objectives of this study are to calibrate and validate the SPACSYS model in terms of grain yield and N removal based on the datasets from the long-term fertilization trials (more than 20 years) located in the north of China; and to assess the effects of various climate change scenarios with fertilization strategies on the yield, N removal and NUE of wheat and maize by 2100 in this region.

2. Methods and materials

2.1. Study site and experimental design

Long-term field experiments (more than 20 years) with a typical double cropping (wheat-maize rotation) from four sites were used in this study. The sites were located in Changping (CP), Zhengzhou (ZZ), Xuzhou (XZ) and Yangling (YL). The long-term experiment in Zhengzhou where it is also located in the study region of northern China has been used to validate the model (Zhang et al., 2016c). In this study, simulated crop yields of ZZ from the previous study were used directly to calculate the average yield of northern China during the prediction period. However, the ZZ site will be treated the same as the

Table 2
Application nitrogen rate for the nitrogen added treatments at four sites (kg ha^{-1}).

Treatment	CP		XZ		YL		ZZ	
	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize
NPK	150	150	150	150	165	188	165	188
NPKM	150 + 146*	150	150 + 237*	150	50 + 115*	188	50 + 115*	188
hNPKM	150 + 218*	150	–	–	74 + 173*	188	74 + 173*	282
NPKS	150 + 18*	150	–	–	165 + 43*	188	123 + 42*	188
Types of Manure	pig		cow		cow		cow and horse	

* The number after "+" indicates the amount from manure or straw.

other three sites for N content in grain and stover and NUE for the prediction (those were not studied in Zhang et al., 2016c). The background information including climatic conditions, soil types and physical-chemical properties from the beginning of the experiments were given in Table 1. The climate in Yangling is warm temperate and semiarid, which is different with other sites. In addition, the experiments at Changping, Zhengzhou and Yangling were irrigated (Table 1), while the experiment at Xuzhou was rain-fed.

All the sites have different fertilizer treatments that can be classified as (i) no fertilizer input (CK), (ii)various combinations of inorganic nitrogen (N), phosphorus (P) and potassium (K) fertilizers (N, NP, NK, PK, NPK) and (iii) inorganic fertilizers plus manure or straw (NPKM or NPKS). Details of experimental design and fertilizer application have been described elsewhere (Duan et al., 2011). Although there are several types of the treatment in the second category, some of them were incomplete in macronutrient supply. Therefore, the datasets from the treatments of CK, NPK, NPKM, hNPKM (1.5 times inorganic NPK fertilizers plus manure) and NPKS were chosen for this study. N input rates and types of all the treatments at four sites are listed in Table 2. In the NPKS treatment of experimental sites, only maize straw was returned because of the limited time between wheat harvest and maize planting, and the maize straw was all returned to plots in NPKS treatment after harvest.

2.2. Model description

Detailed descriptions of SPACSYS have been published previously (Bingham and Wu, 2011; Wu et al., 2007, 2015; Wu et al., 2011). Thus, only a brief summary was presented here. The SPACSYS model is a field-scale, weather-driven dynamic simulation model of plant growth, nutrient cycling and water redistribution, which operates with a daily time-step. The main feature of SPACSYS is the comprehensive and detailed simulation of plant growth and development as well as the root system and the processes associated with soil C and N cycling. The model can simulate CO_2 fixation by a crop canopy and N uptake by a root system simultaneously and their transformation between different crop organs (Wu et al., 2015; Zhang et al., 2016c).

2.3. NUE calculation

In this study, annual NUE from the wheat-maize rotation system was calculated following the previous studies (Duan et al., 2011; Ju and Zhang, 2003; Liu et al., 2003):

$$\mathrm{NUE} = \frac{U_{WN} + U_{MN} - U_{W0} - U_{M0}}{A_{WN} + A_{MN}} \times 100\% \tag{1}$$

where U_{WN} and U_{MN} are N removal including grains and straw (g N m^{-2}) by wheat and maize form a N fertilizer application treatment, and U_{W0} and U_{M0} are N removal by wheat and maize from CK, respectively. A_{WN} and A_{MN} are the amount of N fertilizer application rates (g N m^{-2}) for wheat and maize, respectively.

The stability of wheat and maize yields for each treatment under the RCP climate scenarios and baseline was calculated by their coefficient variation (CV, %) (Berzsenyi et al., 2000; Zhang et al., 2016a). Higher stability is commonly presented by lower variability with low CV (Dobermann et al., 2003). The CV is calcuated as:

$$\mathrm{CV} = \frac{Y_{std}}{Y_m} \times 100\% \tag{2}$$

where Y_{std} is the standard deviation of the grain yield (average of four experimental sites) of a particular treatment during the simulation period and Y_{m} is the mean yield (average of four experimental sites) for the treatment over the same predicted period.

2.4. Weather data and climate change scenarios

Historic weather data for the sites, were downloaded from the China meteorological sharing service system (http://cdc.cma.gov.cn/). In addition, four climate scenarios including baseline, Representative Concentration Pathway (RCP) 2.6, RCP4.5 and RCP8.5 were used for predicting yield and annual NUE of wheat-maize system within northern China between 2015 and 2100. The RCP climate scenarios were adopted by the IPCC (Intergovernmental Panel on Climate Change), which explored a very wide range of radiative forcing levels, in parallel with new work on socio-economic scenarios (van Vuuren and Carter, 2014). The scenarios contain the information about global emissions, the concentration of the greenhouse gases, land-use and land-cover in a global economic framework (van Vuuren et al., 2011). The three RCPs, RCP2.6, RCP4.5 and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5 and +8.5 W/m^2, respectively) (Riahi et al., 2011; Thomson et al., 2011). The annual temperatures and precipitation over the period under the RCP climate scenarios at four sites were given in Table 3. The data were extracted from the HadGEM2-ES model with a spatial resolution of 0.5° × 0.5° (Collins et al., 2011; Jones et al., 2011). The baseline climate scenario was a rotation of historic data during experiment period with a constant CO_2 concentration of 350 ppm at every site.

2.5. Model calibration, validation and prediction

Because the model has been validated on crop yield and N uptake with the data from ZZ (Zhang et al., 2016c), only the datasets from XZ, YL and CP sites were used for calibration and validation in this study. The data on grain yields, N contents in grain and stover at harvest of wheat and maize from the NPK treatment were used to calibrate the SPACSYS model and those from the rest of the treatments for model validation. If a treatment at a site has replicates, an average value of an observed variable over the replicates will be used for the observed value for the given treatment at the site. Sampling numbers for crop yields and N contents in grain and stover at the sites for calibration and validation were shown in Table S1. The MOSCEM-UA algorithm was used for optimization of the model parameter (Vrugt et al., 2003). The calibrated parameters for crop development and N translocation were shown in Table S2. The other parameters were based on the previous studies and not listed in this study (Bingham and Wu, 2011; Wu and

Table 3
Average annual temperature and precipitation with standard deviation (in parentheses) of the RCP scenarios over the period between 2015 and 2100 at four experimental sites.

Climate Scenarios	Maximum temperature (°C)	Minimum temperature (°C)	CO_2 concentration[a] (ppm)	Precipitation (mm)	Precipitation events	Precipitation intensity (> 10 mm)	Precipitation intensity (> 50 mm)
ZZ							
RCP2.6	21(10)	10(10)	431.6	784(185)	10482	1962	80
RCP4.5	22(10)	11(10)	531.2	831(167)	10363	1886	71
RCP8.5	23(11)	12(10)	758.2	933(219)	10375	1971	120
CP							
RCP2.6	18(12)	6(11)	431.6	688(156)	10358	1462	79
RCP4.5	19(12)	7(11)	531.2	684(178)	10045	1408	93
RCP8.5	20(12)	8(11)	758.2	715(156)	10300	1482	104
XZ							
RCP2.6	22(10)	12(10)	431.6	1226(295)	7647	2740	320
RCP4.5	23(10)	12(10)	531.2	1205(297)	7272	2667	308
RCP8.5	23(11)	13(10)	758.2	1251(313)	7806	2713	310
YL							
RCP2.6	20(10)	10(9)	431.6	681(95)	16525	1186	1
RCP4.5	21(10)	11(9)	531.2	663(104)	16001	1114	4
RCP8.5	21(11)	12(10)	758.2	708(117)	15904	1306	7

[a] The CO_2 concentration in 2100.

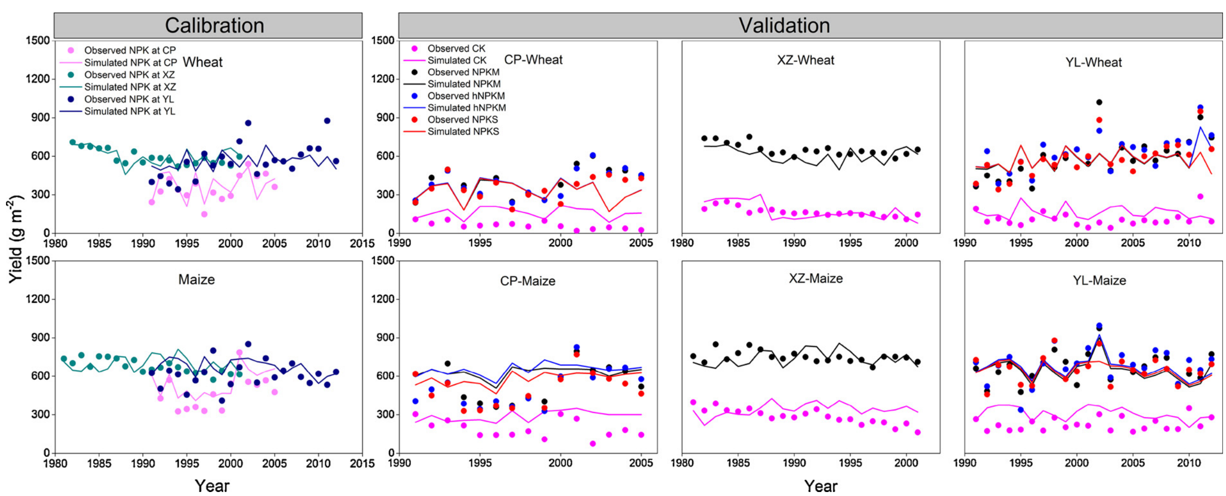

Fig. 1. Simulated and measured yields of wheat and maize over the simulated period at three sites. CP means Changping; XZ means Xuzhou; YL means Yangling.

McGechan, 1998; Wu et al., 2015). For model prediction, crop varieties and field management practices (date and amount of irrigation, seeding and harvesting dates, *etc.*) at a site under each climate scenario are the same as the treatments from the long-term experiment at the site. As the amount of N application with manure amendment at CP and XZ was different from the same treatment at ZZ and YL sites, and the total N application for NPKS was also different at four sites (Table 2), it would be difficult to assess NUE under various climatic scenarios at different sites. Therefore, we justified the amount of N application at CP, XZ and YL to the same amount at ZZ, *i.e.* 165 and 188 kg N ha^{-1} for wheat and maize for NPK, NPKM and NPKS and 247 and 282 kg N ha^{-1} for wheat and maize for hNPKM, respectively.

2.6. Statistical analysis

A set of statistical indexes was used to evaluate model performance (Smith et al., 1997): the coefficient of determination (R^2) that reflects the relationship between observed and simulated values, the root-mean-square error (RMSE) that represents the consistency of observed and simulated values, modeling efficiency (EF) that quantifies how well a model simulation can predict the outcome variable and the relative error (RE) represents the total difference between simulations and measurements. The value of 1 for R^2 or EF and 0 for RMSE or RE corresponds to a perfect match between simulations and observations. Following the previous studies (Christina et al., 2007; Cong et al., 2014; Huang et al., 2013; Liu et al., 2013), we considered that a simulation was eligible when RMSE and RE was less than 15% and 10%, and EF was more than 0.5, respectively.

In order to assess the model performance on simulating annual NUE, one-way analysis of variance (ANOVA) and the least significant difference (LSD) methods ($P < 0.05$) were used to test the difference between simulations and observations under different fertilizer treatments at each site during the experimental period. For the result of the predicted process between 2015 and 2100, two-way ANOVA and Tukey ($P < 0.05$) were used to test the significance of the effects of fertilizer treatments and climate scenarios on average values of crop yields and N contents in grain and stover of wheat and maize, respectively, and annual NUE of the wheat-maize system from four sites. The above statistical analyses were performed by SPSS 20.0 (SPSS, Inc., 2011, Chicago, USA).

3. Results

3.1. Model calibration and validation

The comparison of observed and simulated grain yields and N

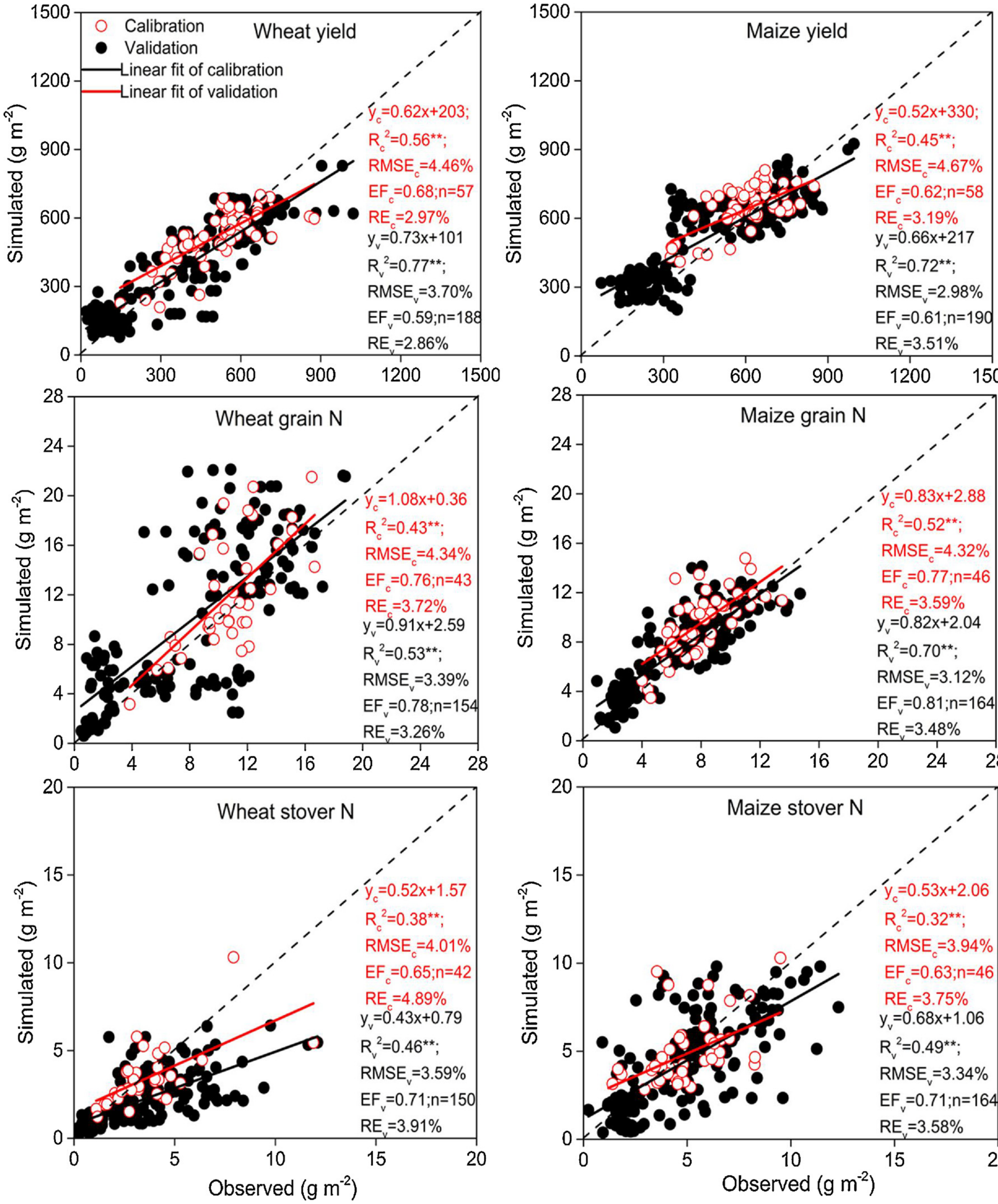

Fig. 2. Relationship between simulated and observed yields, grain N and stem N contents for data from all sites combined (** means $P < 0.01$).

contents in grain and stover at each site was shown in Fig. 1, S1. And the linear regression analysis between observed and simulated data was shown in Fig. 2. Although the statistical test has been past for both calibration and validation, discrepancies between observation and simulation exist. It should be noted that the model overestimated *ca.* 60% of maize yield for the manure and straw incorporated treatments at CP between 1995 and 1999. The simulated values of wheat grain N content at YL site were overestimated by approximately 40%, as the observed and simulated average value was 10.06 g m^{-2} and 14.31 g m^{-2}, respectively (Fig. 1). The linear regression analysis indicated there was an underestimate of 52% and 57% for calibration and validation between observed and simulated wheat stove N contents (Fig. 2).

The comparison of simulated and observed annual NUE of wheat and maize for different fertilization treatments at every site was given in Fig. 3. Simulated NUE for all the fertilization treatments (16–80%) was similar to observed NUE (15–87%), and there was no significant difference between simulated and observed values in most treatments at four sites except NPKS at CP and NPK at XZ.

3.2. *Climate change and fertilization impacts on yield and nitrogen removal*

3.2.1. *Fertilization impacts on crop yield*

Wheat and maize yields (average from four sites) in different fertilization treatments under four climate change scenarios obviously varied (Table 4, Figs. 4 and 5). The average yields of wheat and maize in the fertilized treatments significantly increased (72–100% for wheat and 68–96% for maize) compared with that of CK, and the magnitude of the increments for maize from the fertilization treatments under an

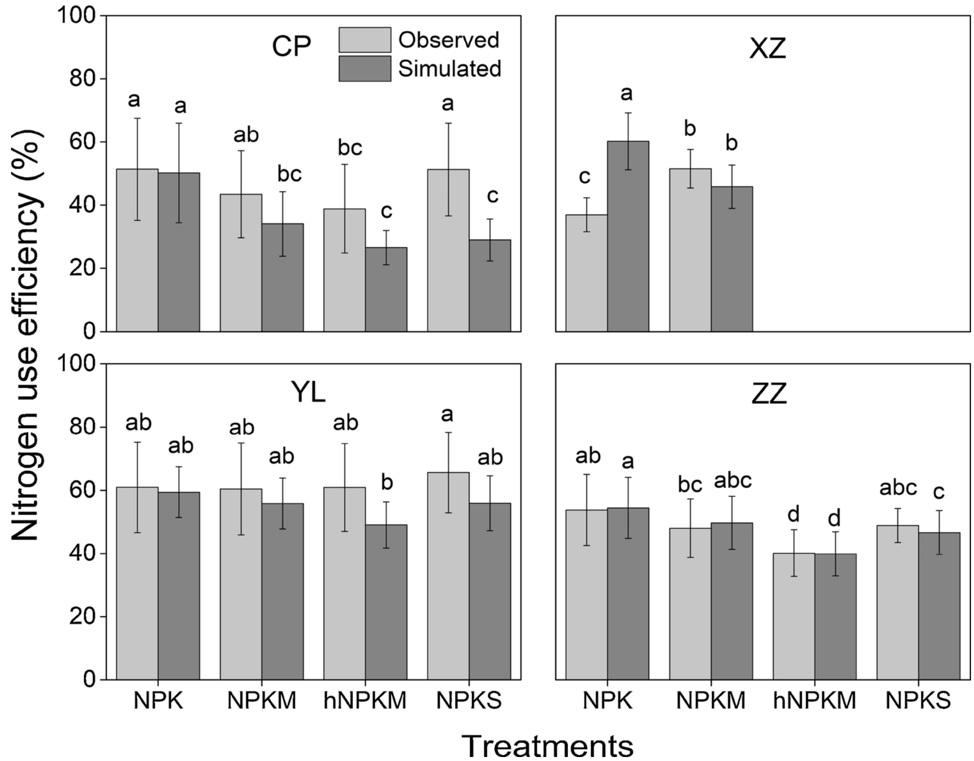

Fig. 3. Average nitrogen use efficiency of wheat and maize system with standard deviation over the simulated period at four sites. The different letters in a row indicate significant difference at 0.05 level for different treatments. CP means Changping; XZ means Xuzhou; YL means Yangling; ZZ means Zhengzhou.

Table 4
Yield and grain N content of wheat and maize, variable coefficient of crop yield and annual NUE (average of four experimental sites) for wheat-maize system in the fertilization treatments under climate scenarios between 2015 and 2100[h].

Treatments	Climate Scenarios	Wheat					Maize					Annual NUE (%)
		Y[a] (g m^{-2})	Y_C[b] (%)	GN[c] (g m^{-2})	GN_C[d] (%)	CV_Y[e]	Y(g m^{-2})	Y_C (%)	GN (g m^{-2})	GN_C (%)	CV_Y	
CK	Baseline	291.36c[f]B[g]	–	6.31aC	–	9.99	379.68abC	–	4.87aD	–	9.01	–
	RCP2.6	364.32aB	26.41	4.59bE	−25.57	12.64	366.52bD	−1.25	4.66aD	−2.18	8.37	–
	RCP4.5	305.54bB	7.77	3.61cE	−41.32	12.20	390.30aD	2.30	4.65aD	−3.92	7.03	–
	RCP8.5	303.51bB	5.29	3.76cD	−39.42	13.63	337.91cD	−10.39	3.46bD	−28.37	13.92	–
NPK	Baseline	569.72bA	–	14.67aA	–	7.82	679.86aB	–	11.62aBC	–	6.00	53.67aA
	RCP2.6	629.07aA	12.11	14.02aB	−1.71	10.28	637.51cC	−5.27	9.38bC	−18.10	5.83	48.21bA
	RCP4.5	574.74bA	2.87	11.56bB	−18.44	11.50	659.08bC	−2.38	9.36bC	−19.21	4.69	43.76cA
	RCP8.5	608.88aA	7.59	10.65bB	−26.53	12.93	590.68dC	−12.85	8.01cC	−30.78	9.35	39.81dA
NPKM	Baseline	567.36bA	–	14.32aA	–	7.75	685.58aB	–	12.22aB	–	6.02	49.02aB
	RCP2.6	628.69aA	12.49	12.85bC	−7.55	10.32	645.11cC	−4.99	10.29bB	−14.85	5.76	43.96bB
	RCP4.5	565.33bA	1.58	10.40cC	−24.72	11.48	666.87bC	−2.00	10.21bB	−16.07	4.60	39.53cB
	RCP8.5	608.41aA	7.95	10.37cB	−26.47	13.35	596.39dC	−12.74	9.35cB	−23.04	8.59	34.79dB
hNPKM	Baseline	571.76bA	–	15.06aA	–	7.82	732.36aA	–	14.47aA	–	6.51	52.78aA
	RCP2.6	627.85aA	11.47	14.69aA	−0.06	10.29	703.57bA	−3.03	11.65bA	−19.31	6.49	48.59bA
	RCP4.5	571.17bA	1.83	12.18bA	−16.53	11.42	741.38aA	2.01	11.97bA	−17.81	5.31	43.78cA
	RCP8.5	609.22aA	7.26	11.48bA	−22.97	12.99	663.10cA	−9.12	10.18cA	−29.43	9.33	38.70dA
NPKS	Baseline	562.75bA	–	12.96aB	–	7.77	675.93bB	–	10.97aC	–	6.97	46.16aC
	RCP2.6	622.35aA	12.35	11.45bD	−11.32	10.33	663.29bB	−0.99	9.50bC	−12.58	6.92	41.81bC
	RCP4.5	565.01bA	2.35	9.31cD	−26.96	11.41	703.39aB	4.99	9.85bBC	−9.40	5.37	37.32cC
	RCP8.5	599.73aA	7.26	8.75cC	−31.65	12.86	625.54cB	−7.04	8.57cBC	−21.38	11.02	32.00dC

[a] Y means average wheat or maize yield (g m^{-2}).
[b] Y_C means relative changes of average wheat or maize yield in the different fertilization treatments under an individual RCP scenario relative to baseline (%).
[c] GN means average N content in wheat or maize grain (g m^{-2}).
[d] GN_C means relative changes of average grain N content in the fertilization treatments under an individual RCP scenario relative to baseline (%).
[e] CV_Y means variation coefficient of average wheat or maize yield (%).
[f] Numbers with different lowercase letters indicate significant difference ($P < 0.05$) under different climate scenarios in an individual fertilization treatment.
[g] Numbers with different capital letters indicate significant difference ($P < 0.05$) in the different fertilization treatments under an individual climate scenario.
[h] The effects of fertilization treatments and climate scenarios on crop yield, grain N content, stover N content and NUE between 2015 and 2100 were shown in Table S3.

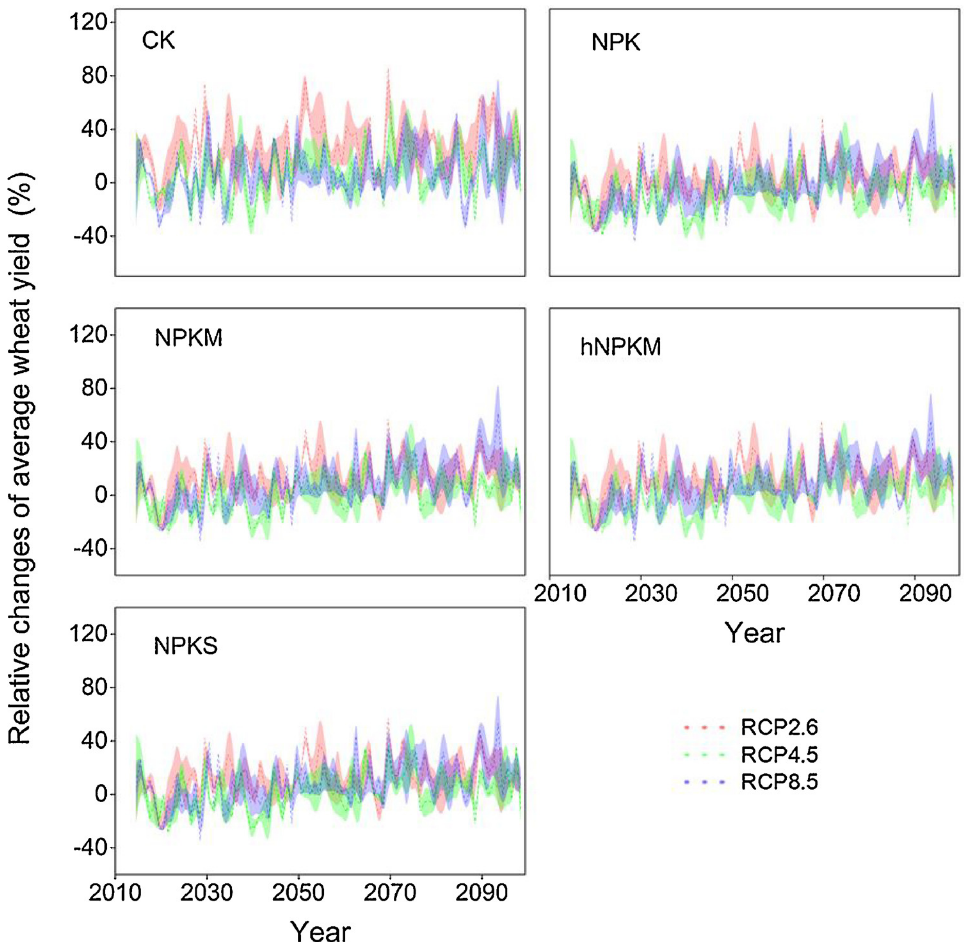

Fig. 4. Dynamics of relative changes of average yield from four sites of wheat (%) with standard deviation under the RCP climate change scenarios among the sites until 2100.

individual climate scenario was ordered as: NPK, NPKM < NPKS < hNPKM (P < 0.05). Fertilization resulted in a more stable yield than CK with lower CV (Table 4) and smaller increment of relative changes over the predicted period (Figs. 4 and 5), especially manure combined with chemical fertilizer for maize.

3.2.2. Climate change impacts on crop yield

Compared with the baseline, the average wheat yield was increased with the relative changes of 1.6–26.4% (average of 8.5%) for all treatments under an individual RCP scenario, and the relative changes of predicted average wheat yield were in increased trends with time over predicted period (Fig. 4). The average wheat yields in the different fertilization treatments under the RCP2.6 and RCP8.5 were significant higher (P < 0.05) than those under the baseline and RCP4.5. In contrast, average maize yield was decreased (average of 3.8%) with time under the RCP climate scenarios between 2015 and 2100, in particularly under the RCP8.5 (average of −10.8%, Table 4 and S3 and Fig. 5). The highest average maize yield among the fertilization treatments was found under the RCP4.5 and the lowest was found under the RCP8.5. In addition, the coefficient of variation (CV) of average maize yield (4.60–13.92%) was lower than that of wheat (7.75–13.63%) under an individual RCP scenario (Table 4).

3.2.3. Fertilization impacts on crop nitrogen removal

Fertilizer amendments significantly increased average N contents of crop grain (an increasing of 105–237% for wheat and 101–197% for maize) and stover (an increasing of 185–337% for wheat and 36–167% for maize) compared with that of CK under an individual climate scenario (Tables 4 and 5 and S3). The highest grain and stover N contents were found in hNPKM for wheat and maize, and maize had a more stable relative changes on both yield and N removal for manure amendment treatments (Fig. S2 to S5).

3.3. Climate change impacts on crop nitrogen removal

The average N contents in grain and stover of wheat and maize were decreased by RCP scenarios in each fertilization treatment during the simulation period, and the greatest reduction in grain N (22.97–39.42% for wheat and 21.38–30.78% for maize) and stover N (32.57–45.40% for wheat and 25.98–36.80% for maize) for each fertilization treatment was found under RCP8.5 (Tables 4 and 5 and S3). The prediction also showed that the reduction of average N contents in wheat grain and stover under RCP2.6 was the lowest among the RCP scenarios in an individual fertilization treatment (Fig. S2 and S4). In addition, average N contents in maize grain and stover under RCP2.6 and RCP4.5 were significant higher than those under RCP8.5 (Fig. S3 and S5).

3.4. Climate change and fertilization impacts on annual NUE

Annual NUEs were averaged from four experimental sites during the predicted period to access the general effects of climate change on wheat and maize, and annual NUEs in the wheat-maize double cropping system under the RCP scenarios were shown in Table 4 and Fig. 6. The RCP climate scenarios reduced NUEs for each of the fertilization treatments compared with the baseline with the following order: baseline < RCP2.6 < RCP4.5 < RCP8.5. In addition, the annual NUE

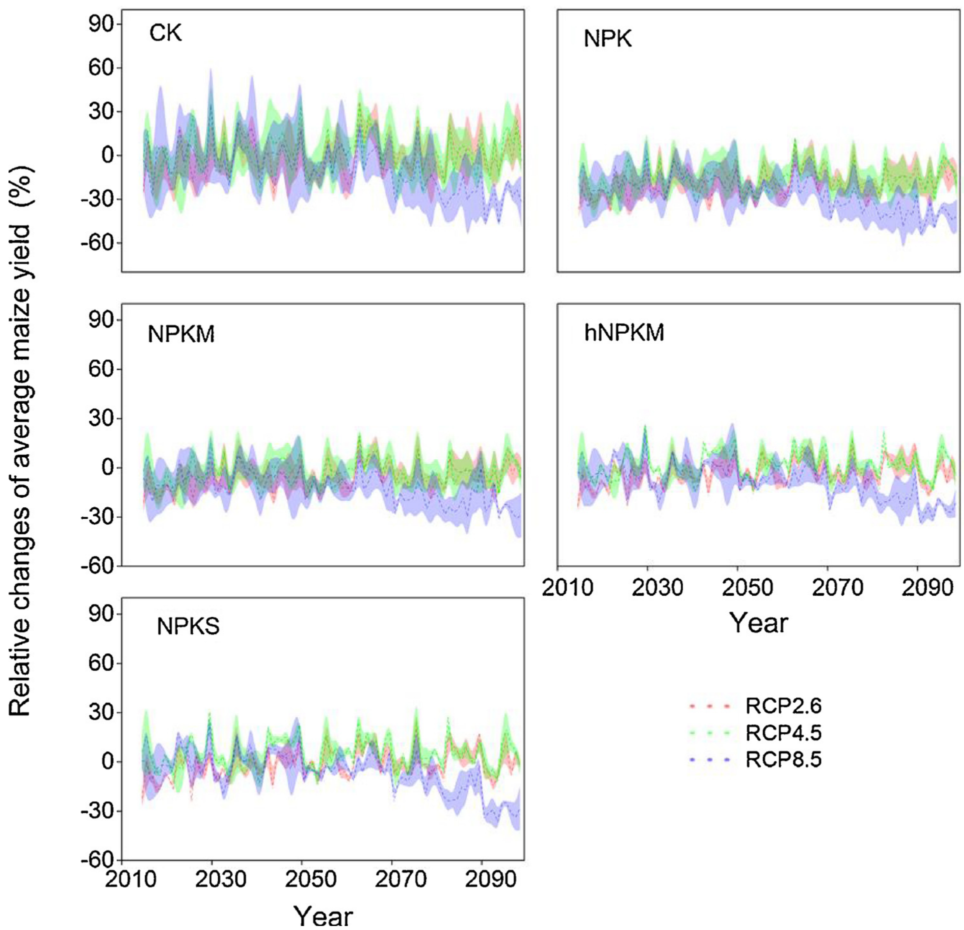

Fig. 5. Dynamics of relative changes of average yield from four sites of maize (%) with standard deviation under the RCP climate change scenarios among the sites until 2100.

with the fertilization treatments under an individual climate scenario was ordered as NPK (39.81–53.67%), hNPKM (38.70–52.78%) > NPKM > NPKS ($P < 0.05$; Table 4 and S3), and the hNPKM had the most stable annual NUE (Fig. 6). The relative changes of annual NUE in NPK and NPKM treatments varied dramatically (ranged from -30% to 30% approximately), while the relative changes of annual NUE in hNPKM and NPKS were smaller (ranged from -30% to 10% approximately) than those in NPK and NPKM treatments under all the RCP climate scenarios.

4. Discussion

4.1. Model performance

The SPACSYS model is able to simulate grain yields, grain and stover N contents of wheat and maize accurately with the R^2 of 0.32-0.77 ($P < 0.05$) for both calibration and validation, which is similar or slightly higher than the R^2 (ranged from 0.40 to 0.72) from the APSIM model on simulating the yields, grain N and biomass N of over-ground part of wheat and maize at the CP, ZZ and YL site (Liu, 2012). In addition, the simulated annual NUE ranged from 16% to 80%, which significantly correlated ($P < 0.05$) to the observed annual NUE (ranged from 15% to 87%). Inevitably, the discrepancies between simulated and observed data still existed. The reasons may due to: (1) the SPACSYS model does not take account of the effects of pests, pathogen diseases and flooding on crop growth; (2) and the differences of nitrogen translocation processes during the reproductive stage for different crop varieties could not be entirely reflected by the model; (3) sampling errors and other events. For instance, plot area changing from a total area of $100 m^2$ with four repeats to a no-repeat plot with the area of $200 m^2$ for the experiments at CP in 1995 may lead to low observed yields (almost 60% overestimation) next year suddenly, as the statistical analysis before 1995 was better than that after 1995 (for example, R^2 was 0.66 and 0.61 for validation of wheat and maize yields from 1991 to 1994, while those from 1995 to 2005 was 0.32 and 0.57). Furthermore, a significant difference ($P < 0.05$) between observed and simulated annual NUE for the NPK treatment at XZ might be caused by the flooding in 1995.

4.2. Climate change and fertilization impact on crop yield

The predictions of the SPACSYS model indicated that application of fertilizers could not only significantly increase wheat and maize yields and N contents of grain and stover but stabilize the yields under either baseline or RCP scenarios until 2100 (Table 4, 5 and S3), which were consistent with previous studies (Gong et al., 2009; Jiang et al., 2006; Liu et al., 2010a; Manna et al., 2007). In particularly, wheat yields were not differed among the fertilization treatments under each climate scenario, which was the same as the historic results between 1990 and 2015 given by Liu et al. (2010b), and the reason might be the total N apply is already meet the requirement of wheat. The maize yield, however, was ordered as NPK, NPKM < NPKS < hNPKM ($P < 0.05$) at the four experimental sites under an individual climate change scenario (with an average of 732.36 $g\ m^{-2}$ for baseline, 703.57 $g\ m^{-2}$ for RCP2.6, 741.38 $g\ m^{-2}$ for RCP4.5 and 663.10 $g\ m^{-2}$ for RCP8.5 for the hNPKM treatment, respectively). This might due to the combination of inorganic and manure or straw could effectively increase soil organic matter and improve soil microbial environment, increasing the number

Table 5
Annual stover N content for wheat and maize in the different fertilization treatments (average of four experimental sites) under climate scenarios between 2015 and 2100.

Treatment	Climate Scenarios	Wheat		Maize	
		Stover N ($g\ m^{-2}$)	Changes of stover N (%)	Stover N ($g\ m^{-2}$)	Change of stover N (%)
CK	Baseline	1.47a[a]C[b]	–	1.84aD	–
	RCP2.6	1.18bD	−14.49	1.77abD	−3.29
	RCP4.5	0.80cD	−42.22	1.72bD	−5.89
	RCP8.5	0.77cD	−44.80	1.26cD	−31.25
NPK	Baseline	4.66aA	–	3.92aB	–
	RCP2.6	4.52aA	1.28	3.47bB	−10.48
	RCP4.5	3.35bAB	−24.66	3.46bB	−10.59
	RCP8.5	2.93cAB	−34.45	2.64cB	−32.01
NPKM	Baseline	4.59aA	–	4.29aB	–
	RCP2.6	4.31aB	−1.91	3.98bA	−6.19
	RCP4.5	3.14bB	−28.35	3.95bA	−6.93
	RCP8.5	2.81cB	−36.52	3.13cA	−25.98
hNPKM	Baseline	4.75aA	–	4.93aA	–
	RCP2.6	4.67aA	2.72	3.98bA	−17.67
	RCP4.5	3.50bA	−23.05	4.00bA	−17.33
	RCP8.5	3.08cA	−32.57	3.07cA	−36.80
NPKS	Baseline	4.23aB	–	2.68aD	–
	RCP2.6	3.65bC	−9.93	2.40bC	−8.64
	RCP4.5	2.67cC	−34.06	2.48abD	−6.23
	RCP8.5	2.21dC	−45.40	1.81cC	−31.20

[a] Numbers with different lowercase letters indicate significant difference ($P < 0.05$) under different climate scenarios in an individual fertilization treatment.

[b] Numbers with different capital letters indicate significant difference ($P < 0.05$) in the different fertilization treatments under an individual climate scenario.

of bacteria, as well as reducing the amount of harmful fungi, which could delay leaf senescence and keep a higher photosynthetic rate (Efthimiadou et al., 2010; Jiang et al., 2006). As a consequent, those promoted the nutrients absorption of crops and crop yields (Zhao et al., 2016; Zhong et al., 2010). It was noted that the yields of NPKM were lower than NPKS, but those of hNPKM were higher than NPKS, so the proper ratio of manure and inorganic fertilizer rates need to be explored for further study. In addition, application of fertilizers resulted in more stable (with lower CV and a smaller increment of relative changes) average grain yields of wheat and maize compared with non-fertilized treatment during the simulation period (Figs. 4 and 5 and Table 4), especially manure combined with chemical fertilizer for maize, because fertilization could decrease the yield variability with the supply of mineral nutrients, such as application of manure (Yan and Gong, 2010). It has been indicated that the improper or unbalanced inorganic fertilizer applications might increase the yield variability, which also influenced by the amounts and types of organic fertilizer (Zhang et al., 2016a). For instance, the CV of average maize yield in hNPKM treatment ranged from 5.31% to 9.33% under four climate scenarios, which was higher than that in NPKM treatment (ranged from 4.60% to 8.59%), and those were lower than that in NPKS treatment (ranged from 5.37% to 11.02%) and CK treatment (ranged from 7.03% to 13.92%). A synthesis analysis of 17 long-term fertilization experiments in China showed that the yield variability of wheat and maize in the NPKM and hNPKM treatments (10–25%) was less than that of the control treatment and NPKS (approximately 35% and 30%, respectively) in the North and North West of China (Zhang et al., 2016a).

For an individual fertilization treatment, the average wheat yields under the RCP2.6 and RCP8.5 scenarios were greater than those under the RCP4.5 and baseline scenarios ($P < 0.05$). However, the average maize yields under the RCP scenarios were all decreased compared with baseline scenario, and the highest (390.30-741.38 $g\ m^{-2}$) and lowest (337.91–663.10 $g\ m^{-2}$) average maize yields were found under RCP4.5 and RCP 8.5 scenario, respectively. For the wheat-maize double cropping system in northern China, there will be an average increase of 8.5% (approximately 99 $g\ m^{-2}$) for wheat and a decrease of 3.8% (approximately 94 $g\ m^{-2}$) for maize by 2100. A simulation study in the North China Plain drew a similar conclusion that winter wheat yield would significantly increase whereas the yield of summer maize would decrease by the end of this century (Mo et al., 2009). It was reported that the optimum temperature of C3 plant for gross photosynthesis was lower than that of C4 plants (Graß et al., 2015), which would lead to

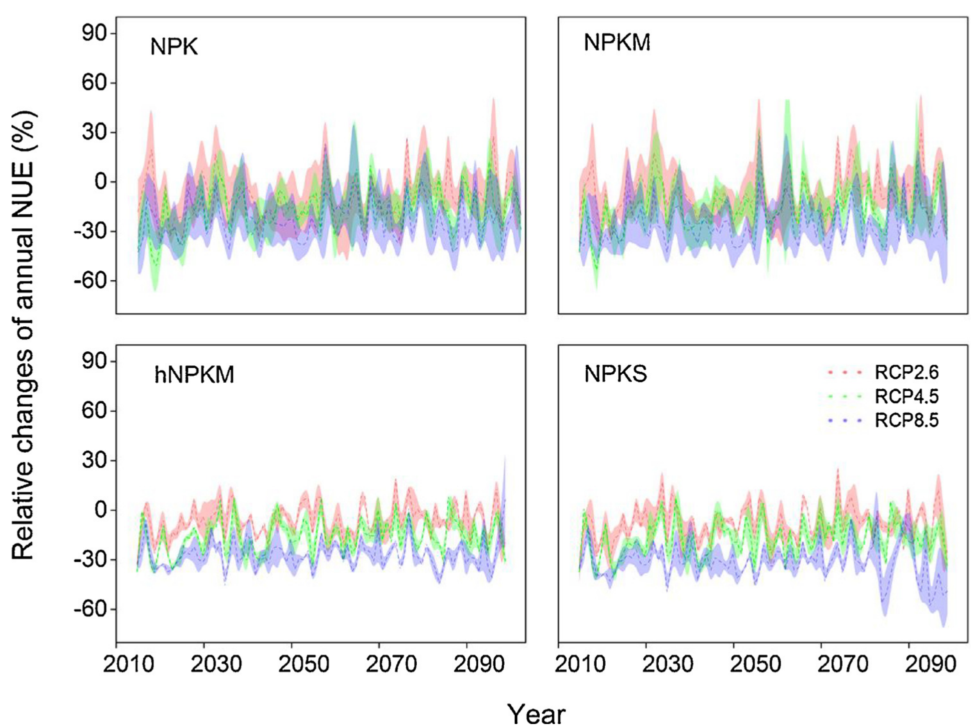

Fig. 6. Dynamics of relative changes of annual NUE (%) under the RCP climate change scenarios among the sites until 2100.

increasing productivity of winter wheat because of warming under climate change scenarios. And a 1.0 °C of warming could result in a 150.0 kg ha^{-1} loss in maize yield in Hebei province, the part of the North China Plain (Chen et al., 2017). As it was mentioned in the field management practices, irrigation might reduce the sensitivity of the crops, especially winter wheat, on the amount and frequency of precipitation events under various scenarios (Xiao et al., 2005). Atmospheric CO_2 concentration increases greatly between the RCP scenarios (Table 3), which could partially explain why the yield of winter wheat increases under the scenarios. The evidences from the experiments indicated that increase in CO_2 concentration could offset the negative effects (even enhance the positive effects) of future climate change on productivity of cereal crop caused due to the 'CO_2-fertilization effect' (Parry et al., 2004). It has been reported that elevating CO_2 concentration to 600 ppm could promote *ca.* 38% of wheat yield compared with ambient CO_2 in the northern China (Guo et al., 2010), and *ca.* 35% from 380 ppm to 700 ppm under 20 °C (Dahal et al., 2014). In addition, it should be noted that wheat yields under the PCP scenarios were higher than that under baseline, while the wheat yield under RCP 4.5 was the lowest and in an order of RCP 2.6 ≥ RCP 8.5 > RCP 4.5 with a 1 °C of annual temperature difference for wheat growth season and enough irrigation for experimental sites (Table 3). The reason might be that the increase in yield by different elevated CO_2 could be negated by increasing temperature. It was reported that the wheat yield would keep increasing until the CO_2 concentrate elevated to 890 ppm concluded by fitting both field and laboratory data (a least squares cubic equation) (Amthor, 2001). However, the wheat yield was decreased by 10–12% under the combination of elevated CO_2 (from ambient to 500 ppm) and temperature (by 1.5–2.0 °C) for a FACE system in the north of China (Cai et al., 2016). A 4 years of experiments also indicated that the increasing in wheat yields (from 598 to 865 g m^{-2} without enhance temperature) from doubling CO_2 (from 360 to 700 ppm) was offset by 2 °C temperature elevating (611 g m^{-2}) (Batts et al., 1997).

4.3. Climate change and fertilization impact on annual crop NUE

For an individual climate scenario, the highest annual NUE with the highest average grain yield and N removal was found in hNPKM at each experimental site, and the manure amendment led to a higher NUE (34.79–52.78%) than NPKS (32.00–46.16%) (Tables 4 and 5). This might due to the manure amendment resulted in a higher N contents in crop organs than that of NPKS (Tables 4 and 5 and Fig.S2 and S3). And the manure amendment maintained a steady and sustainable supply of N (Tong et al., 1997) that might lead to a higher N transferred rate from stover to grain than that of NPKS (Gao et al., 2015). Further, the combination of manure and inorganic fertilization also reduced N loss, which might also result in a higher NUE than that of NPKS. For instance, it had been proved that organic fertilizer can effectively inhibit the accumulation of ammonia volatilization, and manure amendment had a higher decreasing of 9.8% than straw application under the same total N input in northeast of China (Yan, 2016). And manure amendment had a high ability in reducing ammonia volatilization with a reduction of 2/3 through application of manure plus mineral fertilizers compared with chemical fertilizers in a winter wheat planting system of northern China (Gu et al., 2016).

For an individual fertilization treatment, the mean annual NUE was decreased under climate change scenarios following the order: baseline > RCP2.6 > RCP4.5 > RCP8.5 ($P < 0.05$), indicating future climate change would negatively impact (an average decreasing of 9% for XZ, 17% for ZZ and CP and 18% for YL; an average decreasing of 15% for the northern China) on annual NUE of wheat and maize. Future climate changes, including changes of temperature and precipitation, could increase ammonia volatilization from agricultural systems leading to increasing of denitrification rates and N_2O emissions, and the increasing of CO_2 concentration could also promote denitrification through increasing of microbial activity (Butterbach-Bahl and Dannenmann, 2011). Large precipitation intensity could also accelerate the N losses through leaching and surface runoff (Zhang et al., 2016b). Furthermore, the increasing ambient temperature would increase the gaseous N loss to the environment (Pratt et al., 2004). It had been proved that high CO_2 concentration significantly reduced N removal by crops (Li and Kang, 2002). Thus, future climate changes (temperature, precipitation, CO_2 concentration *etc.*) could potentially reduce the annual NUE of wheat and maize through losses of applied N. In addition, climate change can also influence annual NUE through decreasing in N removal by crops. In a maize and wheat rotation, the nitrogen removal was respectively decreased by 31 and 27 kg ha^{-1} when CO_2 concentration at 350 ppm with 3 °C warming (Kaur et al., 2012). It was reported that elevated temperature and water deficit could affect the absorption of N in crops, and reduce the amount of N in the vegetative organs during the functional period, which could further change a series of plant physiological functions and result in the decrease of N transfer rate and grain N content (Li et al., 2005; Sinclair et al., 2000). In addition, drought and excessive precipitation could restrict the soil nutrient supply for crops, which also led to a low N removal of wheat and maize (Buljovcic and Engels, 2001; Patil et al., 2012).

5. Conclusions

The present study indicated the SPACSYS model can simulate crop yields and N removal well for wheat and maize double cropping system in the north of China. For an individual treatment, the RCP scenarios positively changed the wheat yield, while reduced the maize yield for all fertilization treatments until 2100. The RCP climate scenarios could also decrease the annual NUE of wheat and maize double cropping system. Further, inorganic fertilizer combined with manure is effective to sustain the crop productivity and promote crop nitrogen use efficiency under future climate scenarios in the northern China. The highest and most stable annual NUE was found in the hNPKM treatment with the highest crop yields and N removal, and the amendment of manure resulted in a more stable yield and N removal by wheat and maize than other treatments under future climate changes.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.07.019.

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